DESIGN PHILOSOPHIES FOR SAILPLANE AIRFOILS WITH FLAPS

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ABSTRACT

Two different design philosophies for sailplane airfoils with flaps are compared. The first philosophy requires the greatest possible extent of laminar flow on the lower surface for the flap-up case. Because it is difficult to maintain the laminar boundary layer beyond the flap hinge, the flap chord must be small, in the range of 12 to 15 percent of the airfoil chord. For the flap-down case, the upper-surface curvature should be relatively continuous which yields good high-lift performance with 50 to 60 percent laminar flow. This feature results in a concave corner on the upper surface at the flap hinge for the flap-up case. The same is true on the lower surface for the flap down case. These corners cause local separations of the turbulent boundary layer with reattachment occurring aft of the hinge. Experiments have shown no increase in drag due to these turbulent separation bubbles, however. The second philosophy employs a wider flap of 20 to 22 percent chord. It is possible to design these airfoils such that, for the flap-down case, the laminar flow on the upper surface extends to the hinge, followed by a steep pressure recovery. A turbulator is then necessary forward of the hinge to insure attached turbulent flow up to the trailing edge. On the lower surface, the same situation occurs for the flap-up case. The concave corners at the hinge are milder on both surfaces and, for most conditions, the turbulent separation can be prevented in the corners. Examples for both philosophies are presented. Theoretical and experimental section characteristics are compared.

1 - PHILOSOPHY 1

Almost all recent sailplane airfoils with flaps have been designed according to the same philosophy. They have, for the flap-up case the greatest extent of laminar flow possible on the lower surface up to the highest applicable Reynolds number. Usually, it is assumed that laminar flow cannot be maintained across the flap hinge. Therefore, a short flap chord is selected, below 15 percent of the airfoil chord. On the upper surface, a "regular" surface is intended across the flap hinge for the flap-down case. Therefore, a concave corner develops for the flap-up case. The flaps are relatively thin and not too easy to build. The thickness of such airfoils is determined by the extent of laminar flow on the upper surface.

L. Boermans, Ref. [4], designed an airfoil DU 89-134/14 on which the laminar boundary layer extents on the lower surface for the flap-up case even beyond the flap hinge which was realized in wind tunnel tests. D. Althaus presented in Ref. [3] three airfoils AH 93-K-130/15, AH 93-K-131/15, and AH 93-K-132/15, which also have 95 percent laminar flow on the lower surface in the flap-up case.

Examples for philosophy 1 are given in section 3.

2 - PROBLEMS WITH THE DESIGN OF FLAPPED AIRFOILS

The design of airfoils always starts from the specification of their velocity distributions. All design methods define only one shape. This is also true for the multi-point design method, where different parts of the airfoils can be designed for different angles of attack. Airfoils with flaps are more difficult to design because the critical velocity distributions occur for different parts of the airfoils for different flap settings (i.e. different shapes), only one of which can be defined by its velocity distribution. The design of flapped airfoils, therefore, needs some iterations. For example, the design starts with the flap-up case. Then the shape of the resulting airfoil is modified geometrically by introducing a flap deflection. The new shape can only be evaluated using an analysis method, for example, a panel method. The flap deflection changes the velocity distribution over the entire airfoil. The largest changes occur near the flap hinge and near the leading edge. If some boundary-layer developments for the new velocity distributions are not acceptable, it is usually necessary to return to the design method for the original flap setting and to change the input such that the velocity distribution for the new flap setting is changed in the right direction. This often requires many iterations. The most difficult problem exists near the flap hinge. For example, for an airfoil designed according to the philosophy 1 the design is performed for the flap-up case. Then the velocity distribution for the upper surface must be specified such that a concave corner develops near the flap hinge. Only then can the flap-down case produce a smooth velocity distribution near the hinge. This is very difficult to achieve.

3 - IMPROVEMENT OF THE DESIGN PROCEDURE

An improved design procedure is illustrated by means of an example designed according to philosophy 1. Airfoil E 658 has a flap chord of 14 percent of the airfoil chord, and is to have in the flap-up case on the lower surface laminar flow up to the flap hinge for the highest Reynolds number and the lowest lift coefficient that are relevant. Therefore, the airfoil design is performed for this flap-up case and the velocity distribution on the lower surface forward of the flap hinge is specified correspondingly. The pressure recovery begins at the flap hinge aft of which laminar flow is difficult to maintain. This part of the design can be considered somewhat "standard".

For the upper surface, different requirements must be considered:

a) For the flap-up case the laminar flow should extend as far aft as possible.
b) The upper limit of the low-drag range should be as high as possible for the flap-down case and a sharp stall should be prevented.
c) The requirement can only be satisfied if the velocity distribution on the upper surface is in the flap-down case smooth and the boundary-layer separation does not occur more than few percent chord forward of the trailing edge. This requires, for example, for the flap-up case a concave corner developing near the flap hinge.

The first two requirements can be satisfied as described in Ref. [1], for example. The third requirement is satisfied only approximately, as shown in Fig. 1.

Next, an 18° flap down deflection is analysed, for which the upper surface is to be regular near the flap hinge. As in this example, regularity near the flap hinge is normally not achieved. Therefore, the airfoil is smoothed geometrically. In the present example, the smoothing was performed by eliminating the coordinate points near the flap hinge. A cubic spline fit is then computed through the remaining points, which can be used to insert new points. The effect of this smoothing is shown in Fig. 1. The velocity distribution in the pressure-recovery region is nearly linear because this allows high maximum lift coefficient together with gentle stall to be realised.

A second airfoil, E 659 was designed with 95 percent laminar flow on the lower surface for the flap-up case. The flap chord is again 14 percent. Computationally, it is easy to assume that

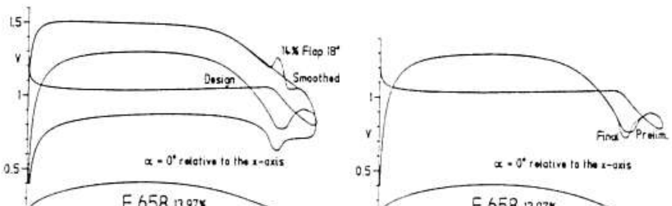

Figure 1: Design of airfoil E 658;
Preliminary and final flap-up case.

the laminar flow "survives" beyond the flap hinge. Practically, the required manufacturing tolerances and the long-term maintenance of this region are another matter.

The design of airfoil E 659 is shown in Fig. 2. The upper surface has again a section with low velocity near the flap hinge. This is in anticipation of the concave corner. The flap-down deflection of 18° again yields an irregular velocity distribution on the upper surface. Moreover, the flap is very thin. The smoothing of the upper surface is therefore performed in a different way. More points are eliminated and one new point is inserted near the flap hinge above the original surface. Then an adequate number of new points is inserted using a spline fit. This makes the flap slightly thicker, although it is still thinner than the flap on airfoil E 658.

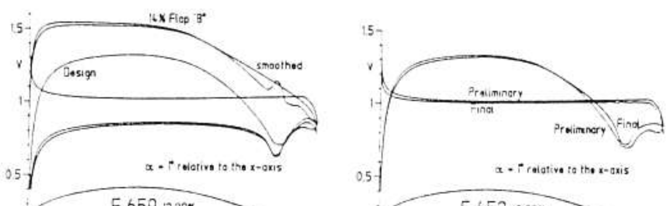

Figure 2: Design of airfoil E 659;
Preliminary and final flap-up case.

Airfoil E 659 is more than one percent thinner than airfoil E 658. This is a significant difference. It is explained by the fundamental fact that the thickness of an airfoil specifies the amount of pressure recovery on both surfaces together, which is necessary for closing the airfoil at the trailing edge. If the thickness remains constant, less pressure recovery on one surface means more on the other surface. Less pressure recovery from both surfaces together means less thickness. The lower surface of airfoil E 659 has less pressure recovery than the lower surface of airfoil E 658 and thus contributes less to the thickness of the airfoil. This requires more pressure recovery on the upper surface which reduces the extent of the laminar flow. The pressure recovery for airfoil E 659 begins about 8 percent chord earlier than on airfoil E 658. Even at 80% chord the thickness is still lower. For obtaining the same thickness as airfoil E 658, the extent of the laminar flow on the upper surface must be reduced further.

The theoretical section characteristics of the two airfoils are shown in Figs. 3 to 8. The Reynolds numbers vary according to the flap deflections. A Reynolds number of 500,000 occurs for a chord of 300 mm at a speed of 86 km/h; a Reynolds number 4,000,000, for a cord of 900 mm at a speed of 229 km/h. The polars thus cover a wide range of chords and velocities. The method used to compute the polars includes the transition criterion and the estimation of the drag due to laminar separation bubbles described in Ref. [2].

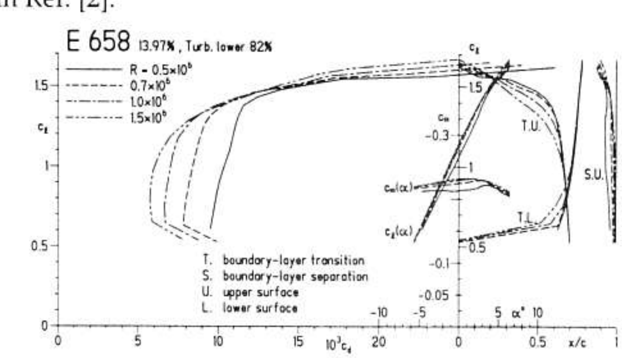

Figure 3: Theoretical section characteristics of airfoil E 658, 0° flap.

For airfoil E 659, the laminar flow extends beyond the flap hinge. This is compensated by the shorter extent of laminar flow on the upper surface. The minimum drag at high speeds is the same for both airfoils. Airfoil E 658 has a slightly lower edge of the low-drag range. At low speeds, airfoil E 658 is noticeably better. This is, however, not significant because the induced drag dominates at low speeds.

Several other airfoils with 95 percent laminar flow on the lower surface have been designed. So far, all attempts

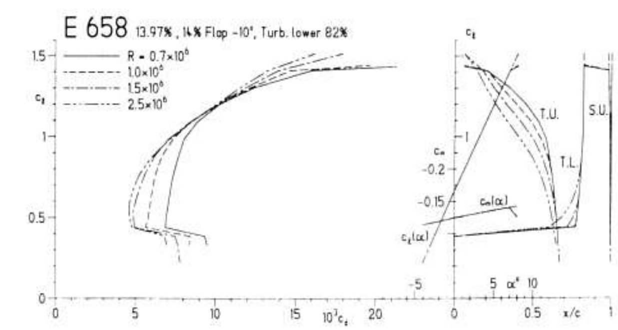

Figure 4: Theoretical section characteristics of airfoil E 658, -10° flap. 5

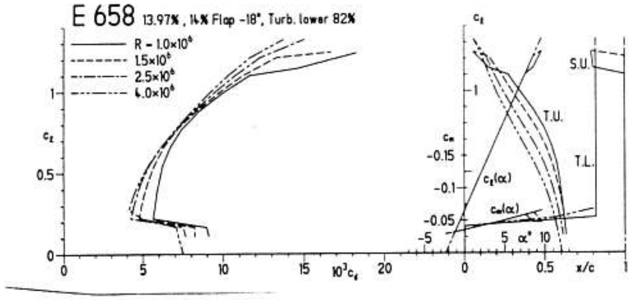

Figure 5: Theoretical section characteristics of airfoil E 658, -18° flap.

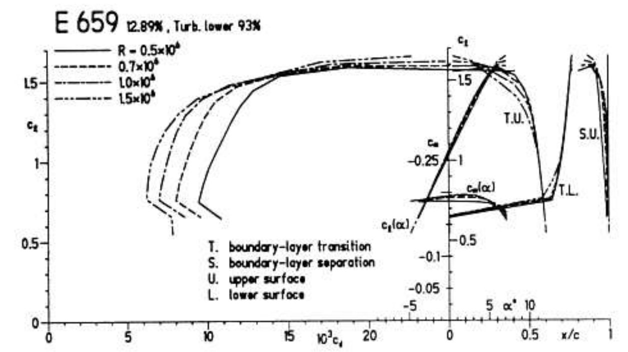

Figure 6: Theoretical section characteristics of airfoil E 659, 0° flap.

showed either less thickness without better performance or less performance with the same thickness. It will be very difficult to design such airfoils such that they have, within the applied theory and under the same conditons for the separation of the turbulent boundary layer advantages over airfoil E 658. Airfoils with laminary flow beyond the flap hinge are therefore not considered further.

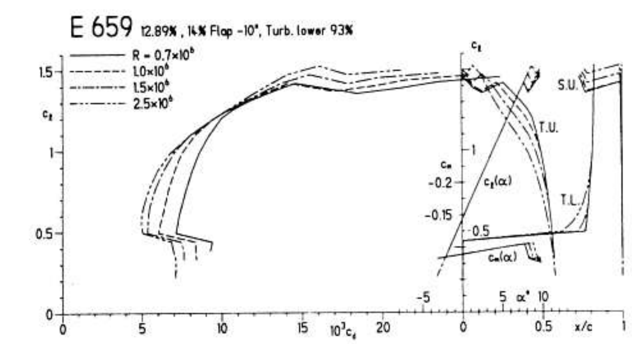

Figure 7: Theoretical section characteristics of airfoil E 659, -10° flap.

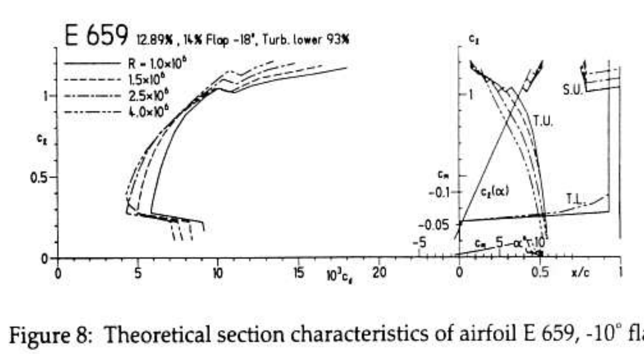

Figure 8: Theoretical section characteristics of airfoil E 659, -10° flap

4 - PHILOSOPHY 2

The main advantage of airfoil E 658 over airfoil E 659 is its longer and greater pressure recovery on the lower surface which allows a greater extent of laminar flow on the upper surface. Design philosophy 2 exploits even more pressure recovery on the lower surface. This is only possible if a longer pressure recovery is specified. There is, thus, no longer any reason to use short flap chords, the flaps become thicker and easier to build with good torsional stiffness. The lower extent of laminar flow on the lower surface again allows a greater extent on the upper surface. An essential feature of philosophy 2 is achieving laminar flow up to the flap hinge on the upper surface for the flap-down case. This requires a steep and large pressure recovery aft of the flap hinge. A turbulator must provide the best initial conditions for the turbulent boundary layer at the beginning of the pressure recovery, which can then overcome the steep pressure recovery. Separation is predicted just forward of the trailing edge, which normally does not cause additional drag. Even if transition moves toward the leading edge at high angles of attack, separation does not occur at the flap hinge. A docile stall can be achieved if the transition does not jump abruptly from the hinge to the leading edge.

Airfoil E 671 is an example of philosophy 2. It was developed in conjunction with airfoil E 658 for the latest sailplane design, B 14, of the Akaflieg Berlin.

It has a 22 percent chord flap. A shorter flap chord would satisfy the requirements of philosophy 2 but with less thickness. The design procedure did not use the improvements discussed in section 3. Instead, the airfoil was designed for a medium flap setting. It took many attempts to achieve the velocity distributions shown in Fig.9. The flap-up case exhibits the desired velocity distribution on the lower surface quite well. The corresponding conditions for the flap-down case are satisfied less precisely on the upper surface. An unintended small depression in the velocity distribution before the beginning of the pressure recovery could not be eliminated. This is not too significant because the flap-down case corresponds to lower Reynolds numbers where such gradients do not easily cause transition. A turbulator must anyway be located slightly forward of the hinge because the transitional boundary layer will separate if the steep pressure recovery begins immediately aft of the turbulator. Some distance is necessary between the turbulator and the beginning of the pressure recovery, for the boundary layer to develop its full turbulence.

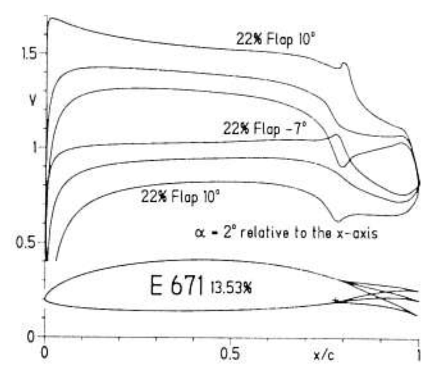

Figure 9: Airfoil E 671 with velocity distributions.

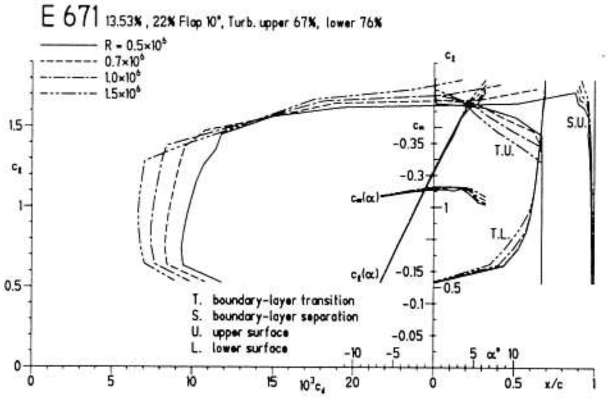

Figure 10: Theoretical section characteristics of airfoil E 671, 10° flap.

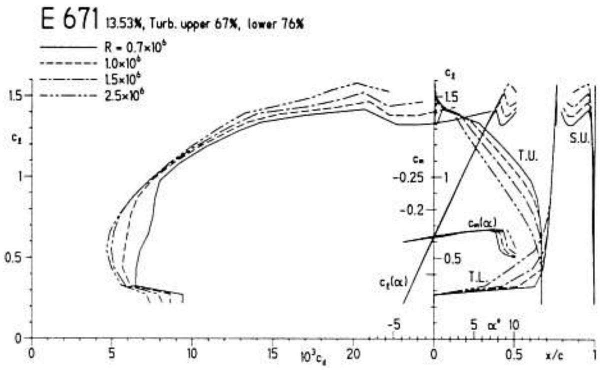

Figure 11: Theoretical section characteristics of airfoil E 671, 0° flap.

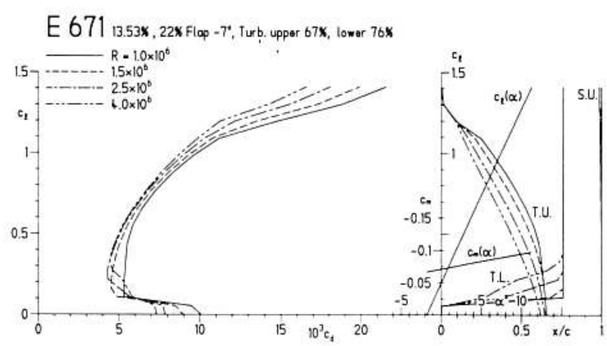

Figure 12: Theoretical section characteristics of airfoil E 671, -70° flap.

The theoretical drag polars are shown in Figs. 10 to 12. Note the differences from the previous polars. Airfoils E 658 and E 659 were defined for the flap-down case, which corresponds to 10° flap down for airfoil E671, a flap deflection of -10° for airfoils E 658 and E 659 corresponds to zero flap deflection for airfoil E 671, and a deflection of -18° flap for airfoils E 658 and E 659 corresponds to -7° for airfoil E 671.

Most interesting is the comparison of the polars for airfoils E 658 and E 671, which correspond to philosophy 1 and 2, respectively. Airfoil E 671 is slightly better at high lift coefficients, which is not significant because the induced drag dominates as previously discussed. For the other flap settings the differences are negligible.

5 - EXPERIMENTAL RESULTS

Airfoils E 671 and E 658 have been tested in the Laminar Wind Tunnel (LWT) of the Institut fur Aero- und Gasdynamik of Universitat Stuttgart, Ref. [3]. This is an open return tunnel with a very low turbulence level and using a rectangular test section 730 by 2730 mm. The drag is measured by means of an integrating wake rake, which is traversed in the spanwise direction to account for drag coefficient variations due to longintudinal inherent structures in the boundary layer. The lift is determined from pressures on the tunnel walls. The pitching moment is measured by a load cell.

The models were manufactured by Akaflieg Berlin with a chord of 500 mm, which is relatively small for this tunnel. This chord allows a Reynolds number of 500 000, which was desirable because the intended application, sailplane B 14, has an 18 m span and high aspect ratio. This low Reynolds number was not tested, however, because the tunnel time was limited. Due to the chord of the models, the highest tested Reynolds number was 2×10^6 which corresponds to velocities below the maximum for the B 14 sailplane.

The results are shown in Figs. 13 to 20. The flap-down cases are shown for low Reynolds numbers, the flap-up cases only for the higher Reynolds numbers. The diagrams are shown in the same sequence as in the previous figures, from the top to the bottom with increasing negative flap setting and Reynolds numbers. The abbreviation ZT in the explanation block means zigzag tape and its location.

Note that the turbulator locations used in the theory and in the experiment are not necessarily the same; the different locations can be seen from the figure key. The locations of the theory are shown in the headline, those of the experiments are noted in the explanations of the line types. If no locations are given there, those of the theory are valid.

Airfoil E 658 shows very little differences for different turbulator locations. Airfoil E671 is more sensitive.

The experimental drag coefficients are slightly higher than the theoretical values, except for high lift coefficients. This may be attributed to some manufacturing tolerances due to the small model chord and to the cover sheets at the flap hinges.

Within the tolerances of the results, the two airfoils both perform remarkably well at high c_l and low Reynolds numbers. At $R = 2 \times 10^6$, airfoil E 658 is slightly better.

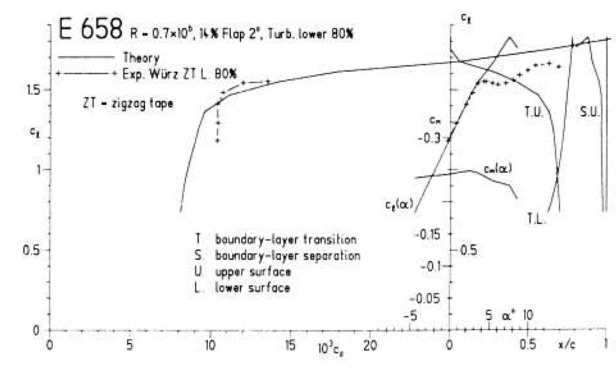

Figure 13: Theoretical and experimental section characteristics of airfoil E 658, 2° flap, $R = 0.7 \times 10^6$.

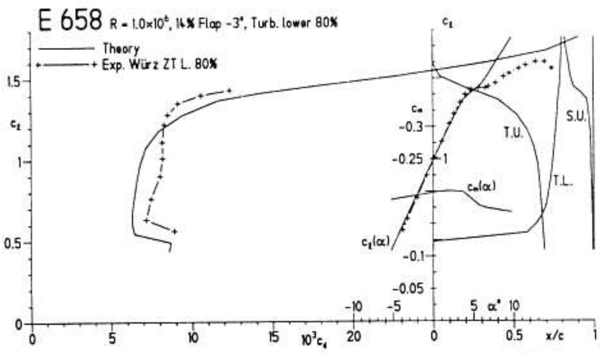

Figure 14: Theoretical and experimental section characteristics of airfoil E 658, -3° flap, $R = 1.0 \times 10^6$.

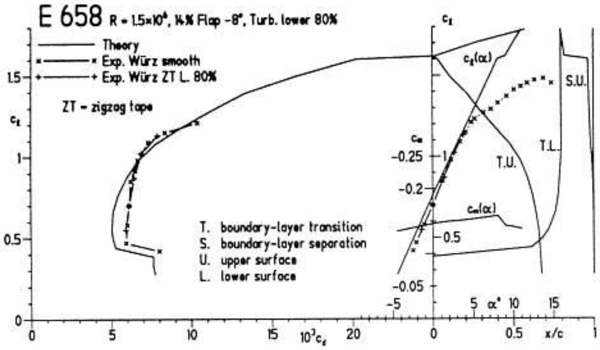

Figure 15: Theoretical and experimental section characteristics of airfoil E 658, -8° flap, $R = 1.5 \times 10^6$.

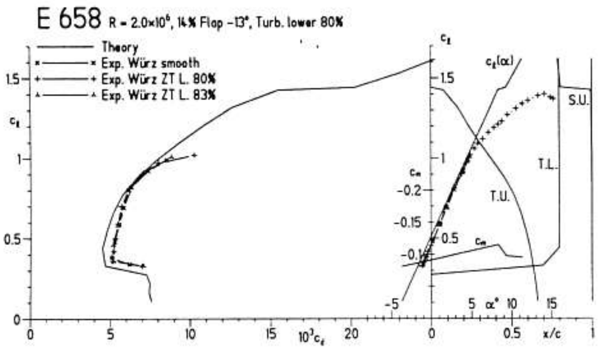

Figure 16: Theoretical and experimental section characteristics of airfoil E 658, -13° flap, $R = 2.0 \times 10^6$.

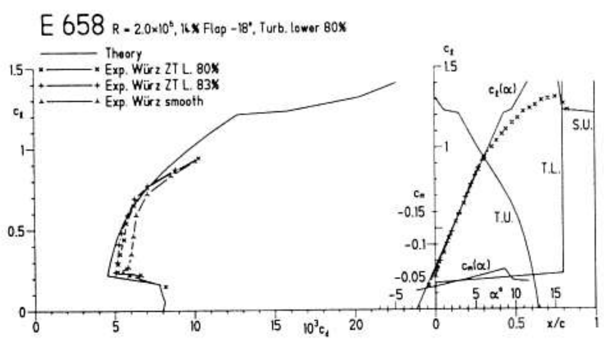

Figure 17: Theoretical and experimental section characteristics of airfoil E 658, -18° flap, $R = 2.0 \times 10^6$.

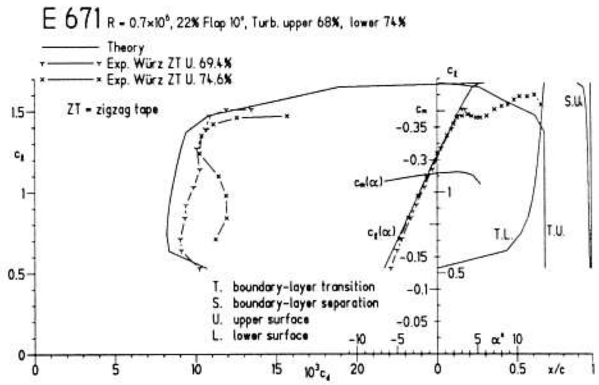

Figure 18: Theoretical and experimental section characteristics of airfoil E 671, 10° flap, $R = 0.7 \times 10^6$.

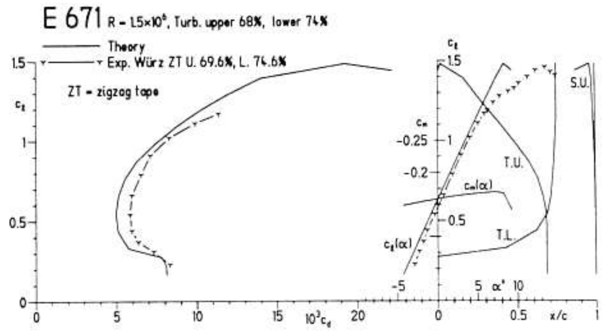

Figure 19: Theoretical and experimental section characteristics of airfoil E 671, 0° flap, $R = 1.5 \times 10^6$.

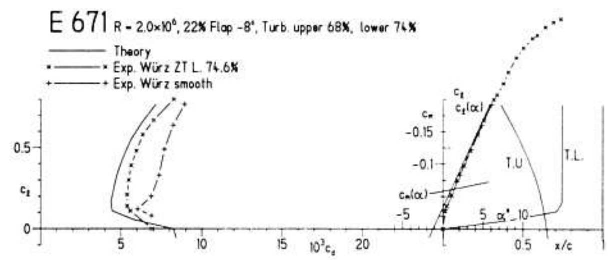

Figure 20: Theoretical and experimental section characteristics of airfoil E 671, -8° flap, $R = 2.0 \times 10^6$.

6 - IMPROVED AIRFOIL USING PHILOSOPHY 2

During the design of airfoil E 671, the improved procedure of section 3 was not used. This procedure was applied in the design of airfoil E 672, as shown in Fig. 21. Again, the preliminary design was performed for a high Reynolds number and a low lift coefficient. This allowed the beginning and the amount of pressure recovery on the lower surface to be specified precisely. Afterwards, an 18° flap-down deflection was introduced and the upper surface was smoothed to obtain the correct velocity distributions for high lift and docile stall. The final airfoil shape is defined in the flap-down configuration. Thus, only negative (flap-up) deflections are relevant.

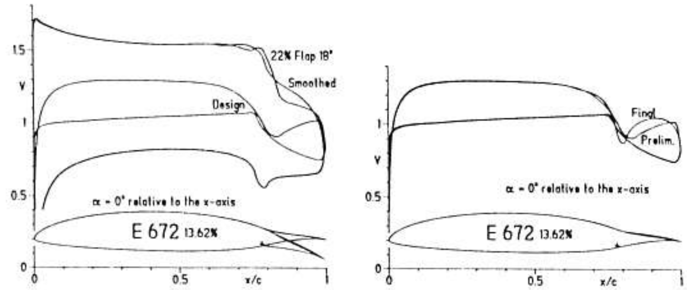

Figure 21: Design of airfoil E 672, preliminary and final flap-up case.

The theoretical section characteristics of this airfoil are shown in figs. 22 to 24. Considerable improvement over airfoil E 671 is achieved, mainly for low lift coefficients and high Reynolds numbers.

Again, a wind-tunnel test of airfoil E 672 has been conducted in the LWT in Stuttgart. The most significant theoretical and experimental results are compared in Figs. 25 to 29. The sequence of the diagrams and the labeling are the same as in section 5. The experiment also showed an

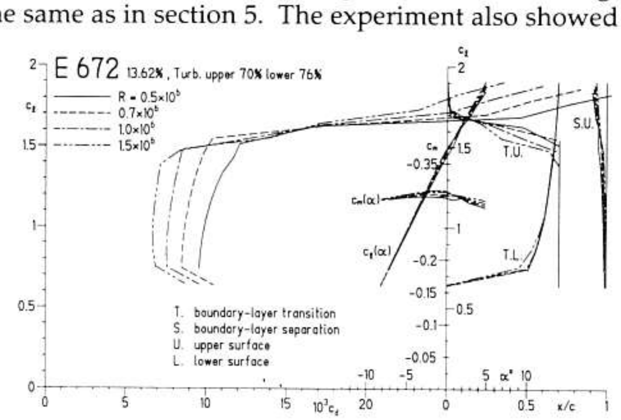

Figure 22: Theoretical section characteristics of airfoil E 672.

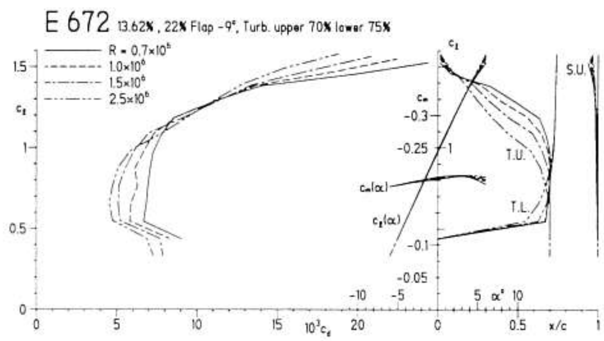

Figure 23: Theoretical section characteristics of airfoil E 672, -9° flap.

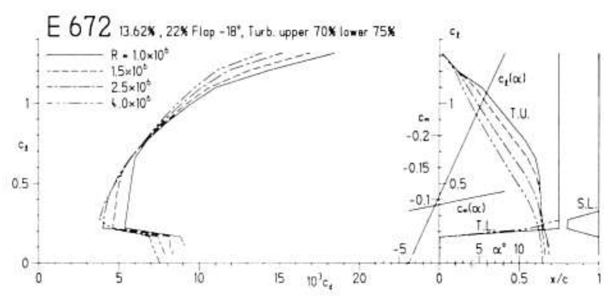

Figure 24: Theoretical section characteristics of airfoil E 672, -18° flap.

improvement over airfoil E 671. For high Reynolds numbers, the drag coefficients are slightly underpredicted, although the limits of the low-drag range are predicted relatively accurate (Figs. 28 and 29). The upper limit of the low-drag range is underpredicted for the high-lift cases (Figs. 25 to 27).

For the Reynolds numbers of 0.7×10^6 and 1.0×10^6 (Figs. 25 and 26), a distinct improvement was achieved by placing a turbulator at about 63% chord on the lower surface. This is a surprising result because the drag of the lower surface at high lift coefficients normally contributes less than 10 % to the profile drag. Apparently, the depression in the lower surface velocity distribution near the flap hinge has a larger effect than expected. This is a problem for all airfoils with flaps because a local separation always occurs near the hinge on the lower surface with a flap-down deflection.

Flow visualization was performed for $R = 1.0 \times 10^6$ and a flap deflection of 0° at cl = 1.37. It shows a laminar separation bubble on the lower surface extending from 63 % to 74.5 % chord. Thus reattachment occurs before the corner produced by the flap deflection. Although flow visualization could not be performed for $R = 0.7 \times 10^6$ because the tunnel speed was too low, reattachment for this Reynolds number probably occurs aft of the flap corner. The effect of the lower surface turbulator is therefore larger for the lower Reynolds number. This effect is not yet understood. Further investigations are necessary to optimize the high-lift case for flapped airfoils at low Reynolds numbers.

The impact of this phenomenon on the wing drag is relatively small at high lift coefficients, however, because the induced drag is around three times the profile drag.

On the other hand, the local turbulent separation on the upper surface in the flap-up case for higher Reynolds numbers did not cause additional drag.

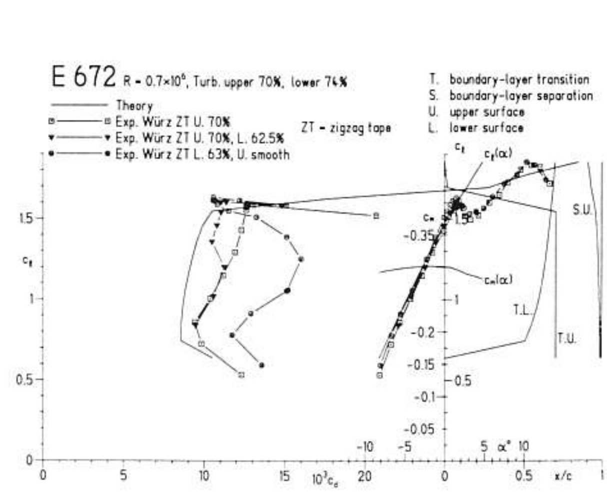

Figure 25: Theoretical and experimental section characteristics of airfoil E 672, 0° flap, $R = 0.7 \times 10^6$.

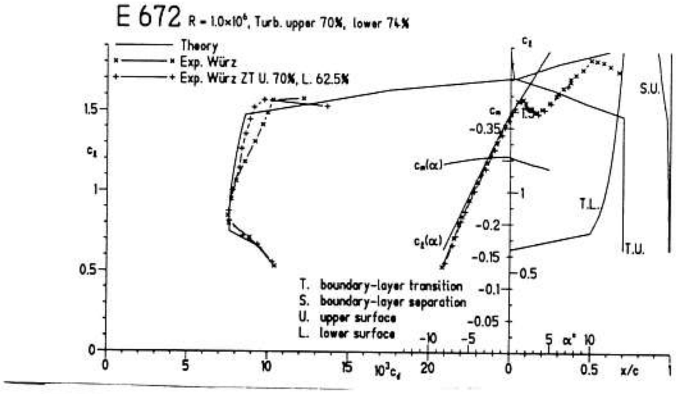

Figure 26: Theoretical and experimental section characteristics of airfoil E 672, 0° flap, $R = 1.0 \times 10^6$.

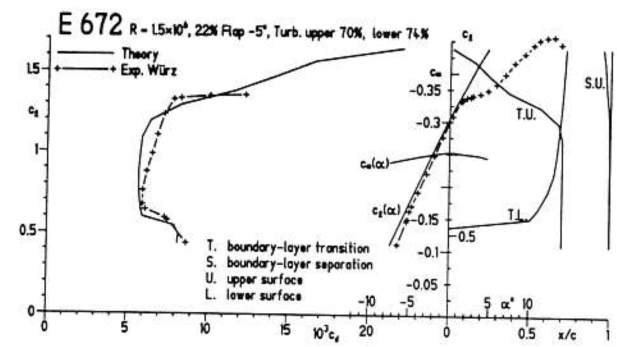

Figure 27: Theoretical and experimental section characteristics of airfoil E 672, -5° flap, $R = 1.5 \times 10^6$.

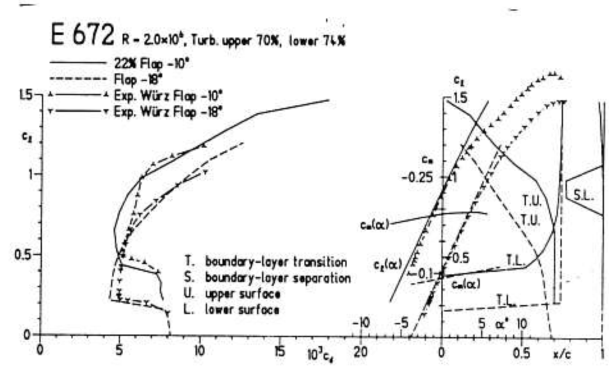

Figure 28: Theoretical and experimental section characteristics of airfoil E 672, -10° and -18° flap, $R = 2.0 \times 10^6$.

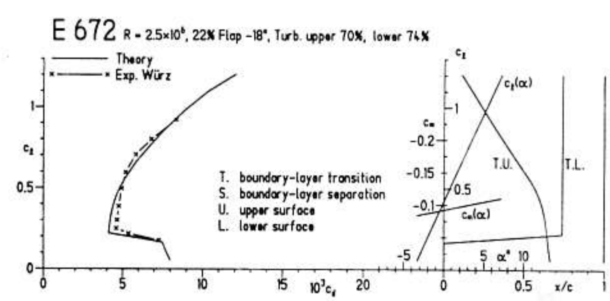

Figure 29: Theoretical and experimental section characteristics of airfoil E 672, -18° flap, $R = 2.5 \times 10^6$.

7 - CONCLUDING REMARKS

Two different philosophies for the design of airfoils with flaps have been discussed. Both of them show promising aspects. Further optimization of the details and further wind-tunnel tests are necessary.

8 - ACKNOWLEGEMENTS

Mr. Sven Kassbohm, Akaflieg Berlin, assisted with the design of airfoils E 658 and E 659 in a very critical and helpful manner. The Akaflieg Berlin built the wind-tunnel models of both airfoils. We really appreciate these activities and thank Sven and the Akaflieg very much.

Mr. Dan M. Somers carefully "translated" our manuscript into his excellent English, and he suggested lots of improvements to the paper.

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